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FLUID POWER RESEARCH CENTER JUN 75 FPRC-5M1
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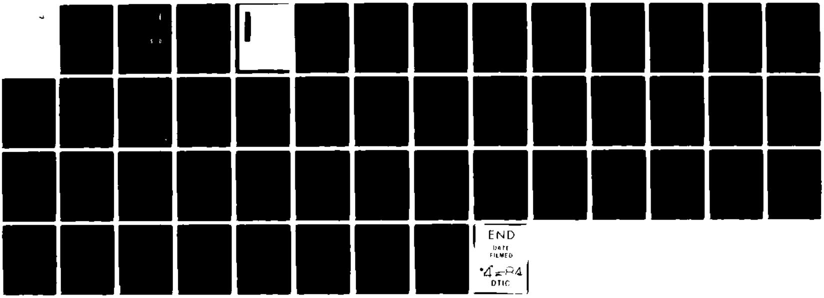

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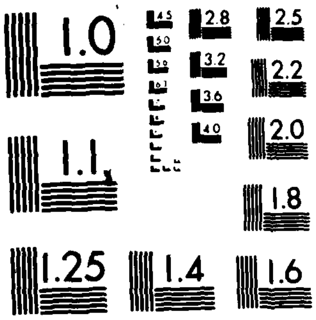

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COMPONENT ENDURANCE

PREPARED BY PERSONNEL OF
FLUID POWER RESEARCH CENTER
OKLAHOMA STATE UNIVERSITY
STILLWATER, OKLAHOMA

June, 1975

FINAL REPORT

June 1974 — June 1975

PREPARED FOR
U.S. ARMY MOBILITY EQUIPMENT RESEARCH
AND DEVELOPMENT CENTER
Fort Belvoir, Virginia

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The purpose of the Oklahoma State University/U.S. Army Mobility Equipment Research and Development Center Program is to provide the military tools for the scientific appraisal of fluid power systems. The activities of the third year of the systems program are a continuation of the efforts of the previous years and make full use of the preceding program. This is the final report for the "*Component Endurance*" project.

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The purpose of this report is to discuss the results of the Hydraulic Component Endurance Study. This study consisted of three phases:

1. **The Acquisition of Component Fatigue Data from Industry**
2. **The Acquisition of Experimental Fatigue Data on Laboratory Specimens**
3. **The correlations of available test data to determine if the *"time at pressure"* during hydraulic component fatigue tests has a significant effect on component endurance life.**

The results show, with 99.5% confidence, that decreasing the *"time at pressure"* during component fatigue tests increases the mean component cycle life by a significant amount for cycle lives greater than 10,000 cycles. It is also shown that the increase in component cycle life due to decreasing the *"time at pressure"* is more pronounced at high cycle lives.

– FOREWORD –

This report was prepared by the staff of the Fluid Power Research Center of the School of Mechanical and Aerospace Engineering, Oklahoma State University of Agriculture and Applied Sciences. The study was initiated by the Mobility Equipment Research and Development Center, Fort Belvoir, Virginia. Authorization for the study reported herein was granted under Contract No. DAAK02-72-C-0172. The time period covered by this report is 1 June 1974 to 1 June 1975.

The Contracting Officer's Representative was Mr. Hansel Y. Smith, and Mr. John M. Karhnak served as the Contracting Officer's Technical Representative. In addition, Mr. Paul Hopler has effectively represented the Contracting Officer both technically and administratively through various phases of this contract. The active participation of Messrs. Smith, Karhnak, and Hopler during critical phases of work contributed significantly to the overall success of the program.

This final report is for the project which was divided into six areas supervised by the following Program Managers:

1.	**Development Phase**	**G. A. Roberts**
2.	**System Operation**	**S.K.R. Iyengar**
3.	**Industrial Liaison**	**R. K. Tessmann**
4.	**Service Life**	**R. K. Tessmann**
5.	**Component Composite Life**	**L. E. Bensch**
6.	**Component Endurance**	**G. E. Maroney**

The results for the first five areas of this study, which were conducted under the general guidance of Dr. E. C. Fitch, Program Director, were disseminated in the Annual Report FPRC-4M5 and conferences with the project monitors.

The purpose of this report is to discuss hydraulic component endurance. The study in this area consisted of three phases:

1. **The acquisition of component fatigue data from members of the fluid power industry**
2. **The acquisition of experimental fatigue data on laboratory specimens**
3. **The correlation of available fatigue test data to determine if the *"time at pressure"* during hydraulic component fatigue tests has a significant effect on component endurance life**

The results show, with 99.5% confidence, that decreasing the *"time at pressure"* during component fatigue tests increases the mean component cycle life by a significant amount for cycle lives greater than 10,000 cycles. It is also shown that the increase in component cycle life due to decreasing the *"time at pressure"* becomes more pronounced as the reference cycle life increases.

This report was prepared by G. E. Maroney, Program Manager, and S. E. Smith, Project Engineer. W. D. Adams served as a Project Associate for this study.

CHAPTER I

INTRODUCTION

The accurate determination of component endurance in a field environment can only be achieved if two sets of data are combined with the proper analytical tools [1]. One data set must reflect the fatigue life of the component under controlled test conditions. The second set of data must adequately reveal the field operating conditions. The analytical techniques which allow projecting a field endurance must account for all of the major parameters which influence fatigue life. In fact, data acquisition for any predictions must be based on sound material failure fundamentals to insure that the proper information is obtained to make the desired projections.

Test procedures for the evaluation of component endurance must be carefully controlled to insure repeatability, reproducibility, and allow meaningful comparisons to be made between competitive products. Only when it has been theoretically verified with statistical significance that particular parameters do not affect test results can the controls on these parameters be relaxed.

It is a widely accepted fact that the maximum pressure during a cycle test of a hydraulic component has a significant effect on the endurance life of the product. But, there is doubt about the significance of effects due to other pressure cycle parameters, such as rise rate, time at pressure, and cycle rate. Material failure literature is replete with discussions of the effects of various wave-form parameters, some of which are supported by a finite amount of new data – many of which reiterate the opinions of other authors giving pseudo-credibility to unsupported hypotheses and some of which draw inaccurate conclusions based on statistically insufficient or insigificant data.

These comments are not intended to detract from the numerous great contributions that have been made to material science by dedicated researchers, but they are intended to

emphasize that the engineering society must always remain objective, for all that glitters is not gold and all conclusions – regardless of how authoritative – are not necessarily true.

There is experimental evidence available in the fluid power industry that indicates that the pressure cycle parameter *"time at pressure"* can significantly affect the mean cycles to failure (MCTF) for a component [1] [2] [3] [4]. If this evidence is statistically significant, then it must be recognized in the development of component fatigue tests and in the prediction of component field endurance life.

The recognition of statistically significant pressure wave form effects on cycle life can be properly achieved by adequate constraints in fatigue test procedures and the pursuit of analytical wave form effect descriptions which can be used for design and service life determination.

The objective of this study was:

> **Initiate a test program to establish the feasibility of *quantitatively evaluating through* "ON-BOARD MONITOR" data the residual fatigue life of hydraulic components as indicated by the strain-time terms of the material failure prediction relation.**

Consistent with the original objective and with the Contracting Officer's Representative's concurrence, it was necessary to establish a statistical level of confidence regarding the effect of pressure wave form *"time at pressure"* on component endurance. Field data from *"ON-BOARD MONITORING"* equipment, such as the statistical analog monitor (STAM) [5] [6], can be meaningfully coupled with laboratory endurance tests only if a proper accounting is made for all of the significant fatigue variables. The average field pressure duty cycle developed from STAM data contains the necessary information to account for not only the maximum pressure per cycle but also the average pressure time exposure of the component. If the wave form effects are significant, proper interpretation of STAM data will allow more accurate projection of field service life than projections based only on maximum pressure per cycle.

This report answers the question, *"Should pressure wave form effects be considered in the assessment of component residual fatigue life?"* The following chapters present the data to be used for addressing this question, delineate the data evaluation, discuss the results of the evaluation, and answer this critical question.

CHAPTER II

DATA

There has been a limited amount of data available in the fluid power industry to show the effect of *"time at pressure"* wave form changes on component cycle life. Once a company converges on a particular fatigue test procedure, there is little propensity to modify that procedure in any manner. This reluctance to change testing methods, which is universal and only varies in degree, exists because changes in test parameters produce changes in test results. If no correlation technique between volumes of *"old"* data and a new proposed procedure is available, an established test facility will lose a *"reference data base"* by transitioning to a new test method. In addition, once a procedure is well established in a testing laboratory, there is rarely enough incentive to run several *"widgets"* under different test conditions because the additional testing requires time and money – plus the fact that the results have to be properly interpreted if the test results are noticeably different.

Prior to 1972, members of the fluid power industry submitted evidence to the Fluid Power Research Center staff indicating that wave form changes do affect component cycle life [2]. Berns' [4] paper in 1973 showed that hydraulic hose failures were also affected by cycle wave form changes of *"time at pressure."* A complete compilation of all these results is tabulated in Table 2-1 as Pump No. 1, Pump No. 2, and Hose No. 1 along with other pertinent data.

During this study, a survey for material failure data was conducted which included over 20 manufacturers and users of fluid power components. One company had data which directly related to the question of wave form effects on component cycle life. J. I. Case Company provided the hydraulic component fatigue data shown in Table 2-2 and summarized in Table 2-1.

TABLE 2-1. Summary of Pertinent Component and Specimen Fatigue Failures [1], [2], [3], [4], [5].

[illegible]	[illegible]		[illegible]		[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
AVERAGE CYCLE LIFE FOR SAME MODE OF FAILURE	[illegible]	4,000	[illegible]	[illegible]	[illegible]	[illegible]
COMPONENT	[illegible]		[illegible]		[illegible]	
CYCLE FORM	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TIME AT PRESSURE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.41
P	2500	2250 psi	2500 psi	2250 psi	[illegible]	[illegible]
AVERAGE CYCLE LIFE FOR SAME MODE OF FAILURE	110,466	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Nos. in parentheses indicate sample size.

TABLE 2-2. Test Data Showing Dependency of Average Cycle Life on Pressure-Time Characteristics of Test Cycle.

		AVERAGE NUMBER OF CYCLES TO FAILURE	
		SLOW CYCLE (2250 PSI MAX)	FAST CYCLE (2500 PSI MAX)
DESIGN CONFIGURATION	A (CYL NO 1)	65,644 Five Samples	110,466 Two Samples
	B	—	145,448 Two Samples
	C (CYL NO 2)	71,811 Three Samples	109,186 Two Samples
	D	—	More Than 644,000 Six Samples

Unpublished test report dated 12 May 1967, J. I. Case Company, Racine, Wisconsin. Mode of failure for failed samples was the same.

As part of the current study, a fatigue test system was constructed in order to obtain more fatigue data where the *"time at pressure"* was a major variable. The fatigue test system, the test specimens, the instrumentation, and the test procedures are discussed in Appendices F through K.

The data set in Table 2-1, labeled *"Sample Set No. 1,"* was obtained at the FPRC on a prototype fatigue test system [5]. Once the fatigue test system was completed, testing was initiated to establish reference cycle lives that could be related to the maximum cycle pressure. During these tests, the wave form, *"time at pressure,"* was varied for at least one specimen at each test pressure. The results of these tests are summarized in Table 2-3.

Industrial liaison indicated that members of the fluid power industry were interested in the effects of *"time at pressure"* for cycle lives in the vicinity of one million cycles to failure. Although it was outside the scope of the contract, a test program was designed to fail a total of eight samples of Lot "A," four at cycles with a *"long time at pressure"* and four at an equivalent pressure but with a *"short time at pressure."* The results

TABLE 2-3. Summary of Fatigue Specimen Mean Cycle Lives, Lot A, T351-2024. Equivalent Test Pressure within a Set.

WAVE FORM DESCRIPTION	SAMPLE SET NO. 2 MARK II LEFT	SAMPLE SET NO. 3 MARK II - RIGHT
"LONG TIME AT PRESSURE"	422,221 Two Samples	132,527 One Sample
"SHORT TIME AT PRESSURE"	767,753 One Sample	159,763 Two Samples

TABLE 2-4. Summary of Fatigue Specimen Mean Cycle Lives, Lot A, T351-2024. Numbers in Parenthesis are Sample Numbers.

WAVE FORM DESCRIPTION	SAMPLE SET NO. 4 MARK II – LEFT	SAMPLE SET NO. 5 MARK II - RIGHT
"LONG TIME AT PRESSURE"	1,036,015 (15) 4,439,731 (22)	*Failure Mode* (8) 120,739 (3)
"SHORT TIME AT PRESSURE"	3,136,174 (5) Over Pressure (23)	120,533 (17) 286,158 (20)

are summarized in Table 2-4. One specimen was inadvertently overpressurized. Another had an unusual mode of failure. The data were not available for analysis prior to publication. The data are only presented here as a matter of interest. The next chapter discusses the evaluation of the data presented in this chapter. Excluding the data in Table 2-4, the failure data in this chapter are presented as mean cycle life to failure for the samples tested in a given facility with a particular wave form. For each data pair, the maximum test pressure was considered the same or the deviation was noted in the appropriate table.

CHAPTER III

DATA EVALUATION

The purpose of this chapter is to evaluate the data presented in Chapter II. Table 3-1 summarizes the data pairs which are ordered from minimum average cycle life to maximum average cycle life.

TABLE 3-1. Ordered Mean Cycles to Failure for "Short" and "Long" Times on Pressure. Modes of Failure the Same for Each Pair.

PAIR NO.	DATA SOURCE	MEAN CYCLES TO FAILURE AT "LONG TIME ON PRESSURE" (N_{i1})	MEAN CYCLES TO FAILURE AT "SHORT TIME ON PRESSURE" (N_{i2})	RATIO OF RAW CYCLE LIVES N_{i2}/N_{i1}	LOG N_{i1}	LOG N_{i2}	RATIO OF LOG CYCLE LIVES $\frac{\text{LOG } N_{i2}}{\text{LOG } N_{i1}}$
1	SAMPLE SET NO. 1	20,870	31,878	1.53	4.32	4.50	1.04
2	CYLINDER NO. 1	65,644	110,466	1.68	4.82	5.04	1.05
3	CYLINDER NO. 2	71,811	109,166	1.52	4.86	5.04	1.04
4	HOSE NO. 1	122,000	216,000	1.77	5.09	5.33	1.05
5	SAMPLE SET NO. 3	132,527	159,763	1.21	5.12	5.20	1.02
6	PUMP NO. 2	150,000	318,000	2.12	5.18	5.50	1.06
7	SAMPLE SET NO. 2	422,221	767,753	1.82	5.63	5.89	1.05
8	PUMP NO. 1	714,000	2,486,000	3.48	5.85	6.40	1.09

Because of the small sample sizes associated with each individual mean life of a data pair, it is unreasonable to expect any statistical analysis within a given data set to yield statistical significance above the 80% level. However, (1) the use of *"pairing"* on the

"*average*" percent increase in the "*life*" or the log* ("*life*") and (2) regression analysis of the same variables provide an accepted statistical technique that accounts for any consistent trends of the data pairs [7] [8]. The use of "*paired*" analysis on the mean cycle life to failure (MCTF) or the log (MCTF) provides an adequate sample size, n, which is so important for establishing statistical significance.

In order to conduct a meaningful statistical analysis, the representative populations must be transformed to another appropriate population, which neutralizes any random effects and allows the analysis to be conducted specifically on the variable of interest. This procedure is accepted and necessary [7] [9].

One transformation commonly used for failure data is to use the log (MCTF) [10] [11] [12]. Working with a log transformation of sample averages improves confidence in the underlying assumption of normality [8].

The ratio of actual MCTF lives for different "*times at pressure*" are listed in Table 3-1 along with the log (MCTF) and the ratio of the log (MCTF) lives. Since the question to be addressed is "*Does cycle time at pressure affect component fatigue life?*" and statistics are unable to accommodate such a direct inquiry, then it is possible to test the hypothesis that "*There is no significant difference due to 'time at pressure'.*" The results of the analysis shown in Appendix A reveal that the hypothesis can be rejected at the 99.5% level when the linear data are analyzed.

Appendix B shows the results of a paired test on the log (MCTF) data. Again, the null hypothesis is rejected at the 99.5% level of significance. Both analyses indicate strongly that the "*time at pressure*" does affect component fatigue life.

Having established that the "*time at pressure*" does affect cycle life, it is interesting to consider the question, "*What is the best estimate of the manner in which 'time at pressure' affects cycle life?*" Before such an estimate of "*the manner in which 'time at pressure' affects cycle life*" is made, it is important to note that only a rough estimate

---

*Log means logarithm to the base 10.

can be made. The data are probably not sufficient to provide the exact relationships needed for life projections. However, regression analysis can provide accurate *"order of magnitude"* information if it is actually contained in the *"raw"* data.

The linear regression in Appendix C on the eight pairs of log (MCTF) yields the following relation between the cycle life for *"Long Time at Pressure,"* X_1, and the cycle life for *"Short Time at Pressure,"* X_2:

$$\mathrm{LOG}\ X_2 = -0.75 + 1.2\ \mathrm{LOG}\ X_1 \tag{3-1}$$

with a coefficient of determination equal to:

$$r^2 = 0.97 \tag{3-2}$$

The regression equation, Eq. (3-1), is an estimate based on all the available data. If some of the data were biased because of other variables in test parameters or if sample sizes are too small (only one) to develop a MCTF, then it is reasonable and practical to exclude any such data to obtain a better regression equation.

Skaistis [14] noted that temperature differences during the tests of Pump No. 1 may have been sufficient to cause the cycle life variations noted. Since the MCTF life for the *"Long Time at Pressure"* was based on one sample and, at *"best,"* there probably was a *"temperature-wave form"* interaction between the tests, it is reasonable to exclude these data from the next analysis.

Since individual MCTF lives for both Sample Set No. 2 and Sample Set No. 3 were based on one sample, it is reasonable to exclude these data sets from further analysis to obtain a regression equation for the effect of *"time of pressure"* on component fatigue life.

Appendix D shows the linear regression analysis for the five sets of data, which include pairs number 1, 2, 3, 4, and 6. The resultant regression equation is:

$$\log X_2 = -0.4 + 1.13 \log X_1 \tag{3-3}$$

The coefficient of determination for Eq. (3-3) is:

$$r^2 = 0.99 \tag{3-4}$$

Appendix B also shows that the 99% confidence limits for the slope (B) of Eq. (3-3) are:

$$1.10 \leq B \leq 1.16 \tag{3-5}$$

The next chapter discusses the analysis results and puts them into perspective relative to component fatigue life determination and fatigue test procedures.

CHAPTER IV

DISCUSSION

The results of the statistical analysis indicate that the *"time at pressure"* affects component fatigue life at the 99.5% level of significance. This confidence in the *"effect"* is reflected in Fig. 4-1, which shows the regression equation, Eq. (3-1), and the eight pairs of data used in the analysis. Fig. 4-1 also reflects the fact that the effect due to *"time at pressure"* is more pronounced at higher cycle lives.

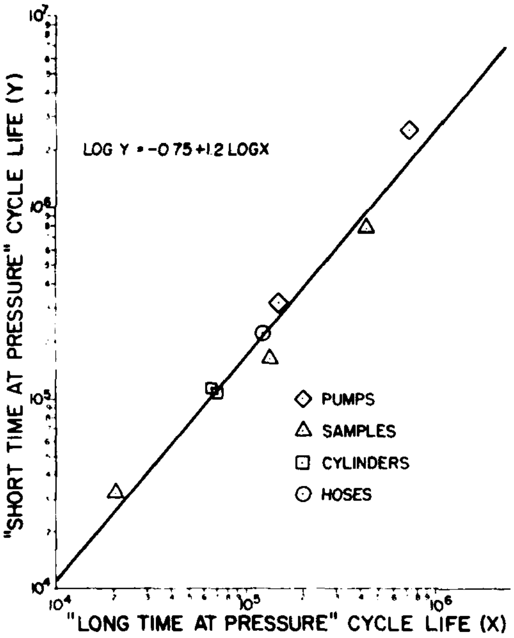

Fig. 4-1. Comparison of Sample Regression Equation and Eight Data Points Showing Variation of Cycle Life Due to "Time at Pressure."

TABLE 4-1. Data Summary for Plotting Cycle Life Ratios Due to "Short" Time at Pressure During Testing. Based on $LOG\ X_2 = -0.75 + 1.2\ LOG\ X_1$ from Eight Data Points.

CYCLE LIFE "LONG" TIME AT PRESSURE (X_1)	LOG X_1	LOG X_2	CYCLE LIFE "SHORT" TIME AT PRESSURE (X_2)	RATIO OF "LIVES" X_2 X_1
100	2	1.65	45	0.45
1,000	3	2.84	692	0.69
10,000	4	4.04	10,965	1.10
100,000	5	5.23	169,824	1.70
1,000,000	6	6.43	2,691,535	2.69
10,000,000	7	7.65	44,668,359	4.47

Table 4-1 summarizes calculations of the ratio of *"lives"* as a function of cycle life, *"Long Time at Pressure,"* (X). These calculations are plotted in Fig. 4-2. This figure indicates that the cycle lives will be approximately equal in some region, in this case in the vicinity of X = 10^4 cycles. In the X region below 10^4 cycles, the regression equation implies that the cycle which has a *"Short Time at Pressure"* will cause component failure the quickest in terms of cycles to failure.

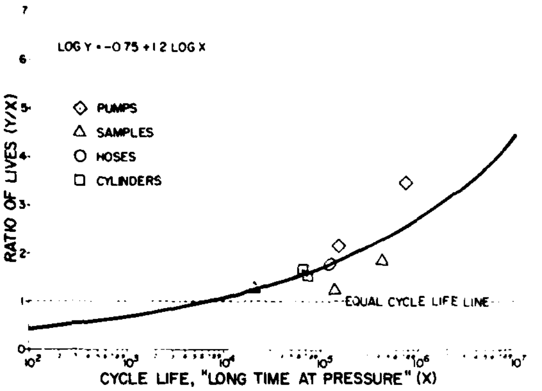

Fig. 4-2. Ratio of "Short" Time at Pressure Cycle Life (Y) to "Long" Time at Pressure Cycle Life (X) Vs. Cycle Life X Based on Eight Data Points.

Although this analysis establishes the significance of *"time at pressure"* effects on fatigue life, insufficient information is available to provide *"exact"* correlation when the times at pressure are precisely defined. In fact, it is reasonable to expect that different ratios of *"time at pressure"* would establish a family of curves such as the one shown in Fig. 4-2. The variation between data sets of the *"time at pressure"* ratio is probably a major cause of the dispersion found in Fig. 4-2.

The analysis results obtained after excluding those data which were assumed to be biased certainly appear to justify the exclusion. Fig. 4-3 visually supports the coefficient of determination of 0.99 obtained for the five data pair.

Table 4-2 shows the data necessary to plot Fig. 4-4. The curve was obtained using regression Eq. (3-3). Fig. 4-4 shows the same general trends as Fig. 4-2. It is interesting to note that the curve shows that the cycle lives are equal in the vicinity of $X = 10^3$. It is pure conjecture, but a reasonable hope, that further exploration and more data would show that the curve is asymptotic to a ratio of cycle lives equal to one. It is entirely possible that some of the data scatter revealed in Figs. 4-2 and 4-4 is due to differences in materials.

One of the most exciting results of this study is the possibility that full recognition of the effects of *"time at pressure"* could reduce the data scatter which often occurs in fatigue tests. The analysis, the resultant graphs, and the tables indicate that *"time at pressure"* variations can significantly affect component cycle life. A slight inversion of Fig. 4-4 allows the construction of Fig. 4-5, which can be used to summarize the analysis results.

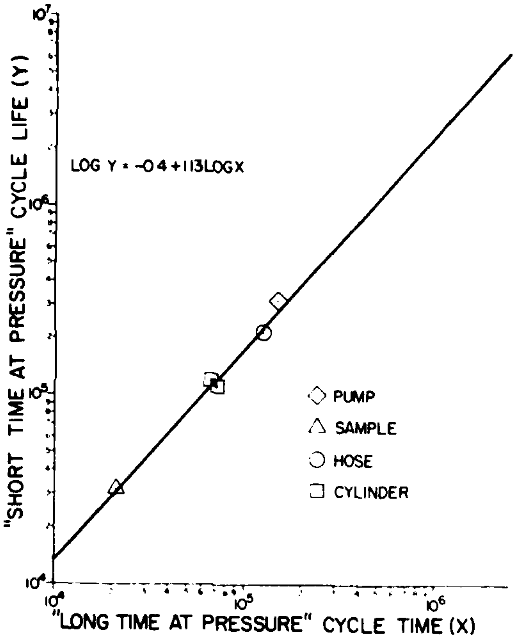

Fig. 4-3. Comparison of Sample Regression Equation and Five Data Points Showing Variation of Cycle Life Due to "Time at Pressure."

TABLE 4-2. Data Summary for Plotting Cycle *Life* Ratios Due to "Short" Time at Pressure During Testing. Based on LOG X_2 = - 0.40 + 1.13 LOG X_1 from Five Data Points.

CYCLE LIFE "LONG" TIME AT PRESSURE (X_1)	LOG X_1	LOG X_2	CYCLE LIFE "SHORT" TIME AT PRESSURE (X_2)	RATIO OF "LIVES" X_2 / X_1
100	2	1.86	72	0.72
1,000	3	2.99	977	0.98
10,000	4	4.12	13,183	1.32
100,000	5	5.26	177,828	1.78
1,000,000	6	6.38	2,398,833	2.40
10,000,000	7	7.51	32,359,366	3.24

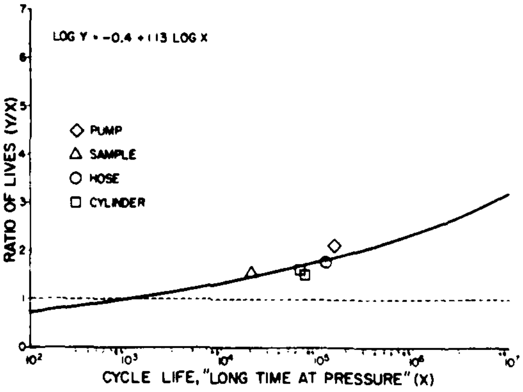

Fig. 4-4. Ratio of "Short Time at Pressure" Cycle Life (Y) to "Long Time at Pressure" Cycle Life (X) Vs. Cycle Life (X) Based on Five Data Points.

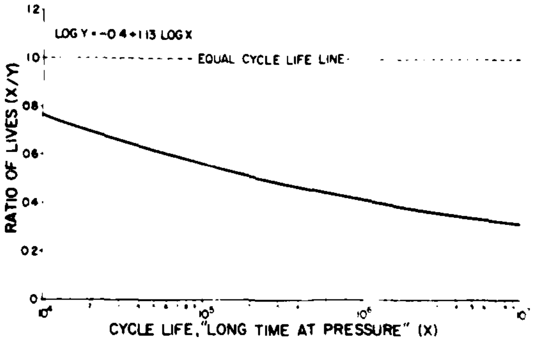

Fig. 4-5. Ratio of "Long Time at Pressure" (X) Cycle Life to "Short Time at Pressure" (Y) Cycle Life as a Function of (X).

Graphs such as Fig. 4-5 could be constructed to be used by system designers for predicting component field life. The construction of such *"design tools"* will be possible once more specific information is available for different materials and for different *"time at pressure"* ratios. Reference to the capabilities of STAM [1][5][6] reveals that STAM data coupled with the proper *"design tools"* will provide designers with an extremely powerful engineering technique for determining component residual fatigue life.

The prediction of residual fatigue life will necessitate definite knowledge regarding a component's fatigue life under controlled endurance tests. It must be emphasized explicitly that, not only must the maximum pressure during endurance cycle testing be controlled, but the *"time at pressure"* must be known and controlled in order for the test data to be used in residual life predictions. In fact, *"time at pressure"* controls must be utilized in component endurance tests if the test results are to be meaningful.

The importance of controlling *"time at pressure"* can be clearly appreciated by considering an example. Suppose component manufacturer A tests all components with a cycle which has a *"time at pressure"* of 0.5 seconds. Further, suppose that component manufacturer B tests all components with a cycle which maintains pressure for 0.1 seconds. If both manufacturers test components one million cycles without failure using the same peak pressure, it does not mean that both pumps have equivalent endurance potential. Reference to Fig. 4-5 reveals that manufacturer B's component is only 46%* as durable as manufacturer A's component. To show equivalent endurance potential, manufacturer B would have to test components at the same pressure level to ($Y = X/0.42$) 2,380,000 cycles. If the reference cycle life was 10^7 cycles for manufacturer A, then manufacturer B would have to test to ($Y = X/0.31$) 32,300,000 cycles.

The faster cycle rate still offers the advantage of completing the test in less time. Consider the $10^6 - 2.38 \times 10^6$ case, where the corresponding cycle rates were 1 - 5. Manufacturer B completes the test in about one-half the time.

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*For $Y = 10^6$, using equation $X = 4.6 \times 10^5$, $X/Y = 0.46$.

CHAPTER V

CONCLUSIONS & RECOMMENDATIONS

This study shows that pressure wave form, in addition to maximum test cycle pressure, should be considered in the assessment of component residual fatigue life. Specifically, hydraulic component fatigue test pressure cycle *"time at pressure"* must be available for the meaningful interpretation of endurance tests. Component fatigue test results and field duty cycles can be utilized for the rational determination of residual component fatigue life only when the *"time at pressure"* for the respective cycles is included in the prediction technique. Since STAM data in the form of an *"equivalent duty cycle"* provides the necessary *"time at pressure"* information, STAM is a valuable data acquisition tool for use in endurance life determinations.

Component fatigue test procedures must include constraints on the pressure wave form's *"time at pressure"* if the resultant data are to be used for qualification purposes, establishing ratings, or determining residual fatigue life.

It is recommended that hydraulic component endurance pressure wave forms be controlled in a manner similar to that used in SAE J343 [15]. If this were done, some latitude could be provided for the cycle rate if the rate were reported with the test results. In order to provide an adequate base for the accurate, confident, prediction of residual component endurance life, it is recommended that the following be pursued:

1. **Establish a test program to provide a correlation of "time at pressure" effects on different materials.**
2. **Establish a test program to provide the correlation between the ratio of cycle lives and the ratio of cycle "time at pressure."**
3. **Plan, implement, and evaluate with actual data the technique for predicting residual fatigue life outlined in Ref. [1].**

ACKNOWLEDGMENT

The staff of the Fluid Power Research Center is extremely grateful to the U.S. Army MERDC for providing an opportunity to identify explicitly a significant source of variation in component fatigue data. The recognition of cycle pressure wave form *"time at pressure"* effects on fatigue life is a significant step toward accurate service life determination. The FPRC staff wishes to thank those members, some who ask to remain anonymous, of the Basic Fluid Power Research Program who contributed data for this study and provided encouragement so often necessary when a hypothesis is being scrutinized.

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APPENDIX A

HYPOTHESIS EVALUATION ON EIGHT PAIRS OF LINEAR DATA

It is desired to test the null hypothesis that *"Wave form does not affect component cycle life."* If the eight sets of data are related as pairs with the *"Long Time at Pressure"* wave form data being set equal to one and the *"Short Time at Pressure"* cycle lives being divided by the mean life of the respective pair, the result is:

Xi2	1.59	1.82	1.21	3.48	2.12	1.77	1.68	1.52
Xi1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
di	0.59	0.82	0.21	2.48	2.12	0.77	0.68	0.52

where di = the deviation between the ith pair. Proceeding with the analysis of the paired experiment [7]:

1. H_0: $\mu_1 = \mu_2$; the means of the two samples are the same.
2. $\alpha = 0.005$
3. $t = (\bar{d}/S_d)\sqrt{n}$

   $\sum di = 8.19$ $\sum di^2 = 13.04$

   $\bar{d} = 1.02$ $S_d = 0.82$

   $t = 1.02/0.82\sqrt{8} = 3.52$
4. Reject null if $t < -3.499$ or $t > 3.499$ from tables for n-1 degrees of freedom.
5. Since $t = 3.52 > 3.499$, reject null hypothesis at 99.5% level.

This means that there is only 0.5% chance the means of the two samples are the same.

APPENDIX B

HYPOTHESIS EVALUATION ON EIGHT PAIRS OF LOG DATA

The data for the paired analysis is [7]*:

Xi2	**1.04**	**1.05**	**1.02**	**1.09**	**1.06**	**1.05**	**1.05**	**1.04**
Xi1	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**

The test is:

1. $H_o: \mu_1 = \mu_2$
2. $\alpha = 0.005$
3. $t = (\bar{d}/S)\sqrt{n}$

   $\sum di = 0.40$ $\qquad$ $\sum di^2 = 0.02$

   $\bar{d} = 0.05$ $\qquad$ $S_d = 0.02$

   $n = 8$ $\qquad$ $df = 7$

   $t = (0.05/0.02)\sqrt{8} = 7.07$

4. Reject the null hypothesis if $t < -3.499$ or $t > 3.499$ from tables for seven degrees of freedom.

---

*Also See Appendix A.

5. Since $t = 7.07 > 3.499$, reject the null hypothesis at 99.5% level.

Because t is over two times larger than the test parameter (3.499), then there is less than 0.5% chance the means of the two samples are the same.

APPENDIX C

LINEAR REGRESSION & REGRESSION COEFFICIENTS FOR EIGHT PAIRS OF LOGARITHMIC DATA

The paired data to be curve fitted are:

X2	4.50	5.04	5.04	5.33	5.20	5.50	5.89	6.40
X1	4.31	4.82	4.86	5.09	5.12	5.18	5.63	5.85

where: X2 = log (mean cycle life wave form 2)
X1 = log (mean cycle life wave form 1)
n = sample size (8)

The basic equation form is:

$$y = A + BX \qquad \text{(C-1)}$$

for this case

$$\text{LOG X2} = \text{LOG C} + \text{D LOG X1} \qquad \text{(C-2)}$$

Using a linear regression program, the coefficients are:

$$A = -0.75$$
$$B = 1.2$$

The equation then which describes the relationship between the two data sets is:

$$\text{LOG X2} = -0.75 + 1.2 \text{ LOG X1} \qquad \text{(C-3)}$$

The coefficient of determination [13] or the square of the sample estimate of the correlation coefficient [8] is:

$$r^2 = 0.97$$

The null hypothesis that the correlation coefficient (ρ) is equal to zero can be tested at the 1% level of significance by referring to Table A11 of Ref. [2]. This means:

1. H: $\rho = 0$
2. $\alpha = 0.01$
3. $r_{\text{calculated}} = r_{\text{cal}} = 0.98$
4. degrees of freedom $= n - 2 = 8 - 2 = 6$
5. Reject H if $r_{\text{table}} < r_{\text{cal}}$.
6. $r_{\text{table}} = 0.834$
7. $r_{\text{cal}} > r_{\text{tab}}$ $\therefore$ reject the hypothesis

Specifically, this means that we are 99% certain that the equation based on the data establishes a good correlation between X_1 and X_2.

Now, it is appropriate to ask *"How confident can we be that ρ is 0.98?"* This question is resolved as follows [8]:

1. $r = 0.98$ (Sample Estimate of Correlation Coefficient)
2. $n = 8$
3. From tables, $Z = 2.298$.
4. $\sigma_Z = 1/\sqrt{n - 3} = 0.48$
5. Desire 99% confidence limits on ρ
6. $Z_{0.01} = 2.576$
7. $2.298 - (2.576)(0.45) \leq Z \leq 2.298 + (2.576)(0.45)$

   $$1.14 \leq Z \leq 2.58$$
8. From tables:

   $$0.814 \leq \rho \leq 0.989$$

This means that there is only a 1% chance that ρ is less than 0.814.

Since a D of 1.0 would imply a one-to-one linear relationship between X_1 and X_2, it is reasonable to determine 99% confidence limits for D [8]:

1.

X_2	4.50	5.04	5.04	5.33	5.20	5.50	5.89	6.40
$\hat{Y}$	4.42	5.02	5.07	5.34	5.38	5.45	5.99	6.25
d	.08	.02	-.03	-.01	-.18	.05	-.10	.15
d^2	.01	--	--	--	.03	.01	.01	.02
d^2	.08							

2. $S_{yx}^2 = \sum d^2/n\text{-}2 = .08/6 = 0.013$

3. $S_b^2 = S_{yx}^2/\sum X^2 = .013/210$

   $S_b = 0.008$

4. $\alpha = 0.01$

5. $b - t_{0.01} S_b \leq \beta \leq b + t_{0.01} S_b$

   $1.2 - (3.169)(.008) \leq \beta \leq 1.2 + (3.169)(.008)$

   $1.2 - 0.03 \leq \beta \leq 1.2 + 0.03$

   $1.17 \leq \beta \leq 1.23$

This means that there is a 99% chance that the actual slope, β, of the equation:

$$\text{LOG } X_2 = A + D \text{ LOG } X_1 \qquad \text{(C-1)}$$

is greater than 1.17.

Thus, the following can be stated with greater than 99% confidence:

> *"The time at pressure during a cycle does affect fatigue life as measured in cycles, and the effect is more pronounced at higher cycle lives. The influence is such that a shorter time at pressure tends to increase the cycle life in the life region above 10^4 cycles."*

APPENDIX D

LINEAR REGRESSION & REGRESSION COEFFICIENTS FOR FIVE PAIRS OF LOGARITHMIC DATA

The paired data to be curve fitted are:

X_2	4.50	5.04	5.04	5.33	5.50
X_1	4.32	4.82	4.86	5.09	5.18

The symbols are defined in Appendix C. The resultant equation is:

$$\text{LOG } X_2 = -0.4 + 1.13 \text{ LOG } X_1$$

The coefficient of determination is:

$$r^2 = 0.99$$

Certainly, $\rho \neq 0.0$.

The 99% confidence limits on ρ are:

1. $r = .995$
2. $n = 5$
3. $Z = 2.994$
4. $\sigma_z = 1/\sqrt{n-3} = 0.707$

5. $Z_{0.01} = 2.576$

6. $2.994 - (2.576)(0.707) \leq Z \leq 2.994 + (2.576)(0.707)$
$2.994 - 1.821 \leq Z \leq 2.994 + 1.821$
$1.173 \leq Z \leq 4.815$

7. $0.825 \leq \rho \leq 0.995$

The 99% confidence limits for the slope of the equation are:

1.

X_2	4.50	5.04	5.04	5.33	5.50
$\hat{Y}$	4.48	5.04	5.09	5.35	5.45
d	.02	.01	.05	.02	.05
d^2	--			–	—
d^2	.01				

2. $S_{yx}^2 = \sum d^2/n\text{-}2 = .01/3 = .003$

3. $S_b^2 = S_{yx}^2/\sum X^2 = .003/118$

$S_b = .005$

4. $\alpha = 0.01$

5. $b - t_{0.01} S_b \leq \beta < b + t_{0.01} S_b$
$1.13 - (5.841)(0.005) < \beta \leq 1.13 + (5.841)(0.005)$
$1.13 - (0.03) < \beta < 1.13 + (0.03)$
$1.10 \leq \beta \leq 1.16$

APPENDIX E

MARK II FATIGUE TEST SYSTEM

The *"Mark II Fatigue Test System"* is shown in Figs. E-1 and E-2. The test stand tests two specimens at the same time, with each specimen given independent parameter control. A specimen ready for testing is clamped into a vise, Fig. E-3. A pneumatic cylinder exerts a force on the end of the specimen in a direction perpendicular to its axis. This force is controlled by the pneumatic pressure inside the cylinder. Because the piston has a one square inch area, there is an approximate one-to-one relationship between the air pressure in psi and the force exerted in pounds. This air pressure is controlled by a solenoid valve, Fig. E-4, which is cycled by a cycle timer

The resulting wave form is trapezoidal, with the rise and decay times being approximately equal. The *"pressure on"* and *"pressure off"* times can be controlled on the cycle timer, and the peak force applied at the end of the specimen is varied with the air pressure relief valve.

The force applied is uni-directional, so the specimen is stressed essentially the same as a hydraulic component. Test system variations are neutralized by calibrating both sides

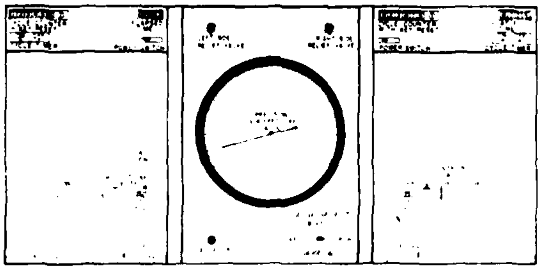


Fig. E-1. Frontal View of Mark II Fatigue Test System.

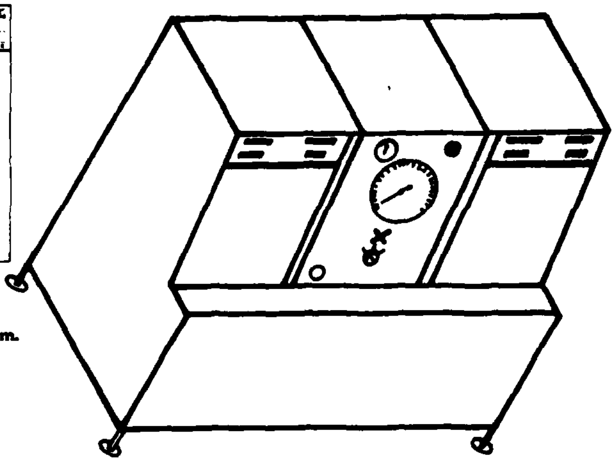


Fig. E-2. Perspective Drawing of Mark II Fatigue Test System.

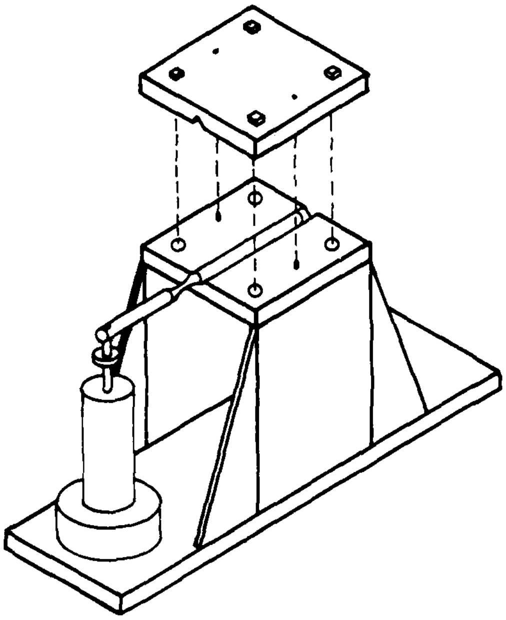


Fig. E-3. Enlarged View of Fatigue Specimen Support Structure and Load Cylinder.

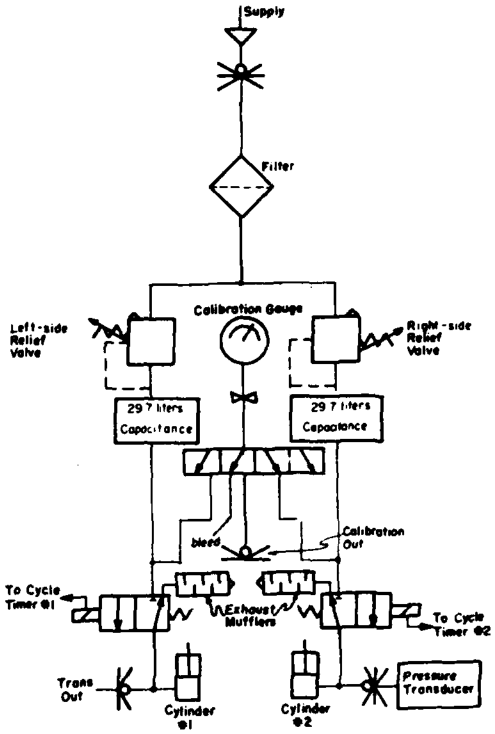


Fig. E-4. Mark II Fatigue System Pneumatic Schematic.

to *"each other"* with a force transducer. A simple but accurate transducer for this purpose is made by applying a strain gauge on the top of a specimen and then correlating the air pressure required on the left side to cause the same dynamic strain produced by a certain air pressure on the right side.

The design of the Mark II Fatigue Test System was refined and calibrated continually during its construction, when practice runs showed flaws and unexpected deviations in data. The major difficulty encountered was that the left side did not produce the same force as the right side at the same air pressure. This difference was eliminated by using a calibration specimen, fitted with strain gauges, on each side. Because of the position of the gauges, the air pressure needed to give the same force was found by making their strain cycles equivalent on an oscillograph recorder. It is very important to note here that the

side-to-side correlation is performed dynamically during an actual test cycle, so that any static effects which aren't present during the testing will not affect the correlations. It was found that the left side needs 18.2 psi to exert the same specimen strain that 17.5 psi on the right side produces.

The pneumatic capacitance beneath the cylinder piston is minimized to give a fast response. This is accomplished by keeping the piston low and by placing the solenoid valve very close to the piston. The air pressure cycle, which is directly related to the strain cycle, and thus the force cycle is monitored with a dynamic pressure transducer. The transducer can be *"placed in"* or *"taken out"* of the system with a quick-disconnect fitting.

Some concern was expressed during the early stages of testing as to the relationships of the tensile and compressive stresses on the specimen (i.e., the bottom and top surface stresses at the middle of the notch). Strain gauges were placed in the critical areas of the notch on the top and bottom to find this correlation. An oscillograph measurement showed that there is definitely direct relationship between these tensile and compressive stresses.

The dynamic response of the pneumatic system was observed to degenerate when small relief valves were used for regulating the air pressures. Initially, small precision relief valves were employed but were found to regulate no better dynamically than larger valves, and they seriously altered the wave form. Due to their low flow rate capability, the resulting wave form was severely rounded and erratic. However, the large flow rate valves exhibit a small, but annoying, amount of drift. As the pressure was applied, the peak pressure drifted to higher pressures the longer it was activated. This problem was solved by inserting a 27 litre pneumatic capacitance between the relief valve and the solenoid valve.

The accuracy in mounting the piston perpendicular to the specimen was deemed to have an effect on the test results. The desired right angle was achieved by shimming the base of the cylinder by thousandths of an inch, cycling a calibration specimen, and watching for residual strain readings when the air pressure was *"off."* Because of internal friction

and machining tolerances in the piston, there was a certain amount of strain left on the specimen. That strain was minimized by adjusting this perpendicularity, lubricating the piston seals, and lubricating the contact between the piston rod end and the rod guide hole in the specimen.

Detailed check lists which are used for calibration and for conducting fatigue tests are listed in Appendices J and K. A list of instrumentation used with the fatigue test system and information regarding strain gauges is included in Appendices I and H, respectively.

APPENDIX F

SPECIMEN CONFIGURATION

The specimen design used for this test program is pictured in Fig. F-1. Specimens are made from 1/2 inch bar stock of aluminum T351-2024. This alloy was chosen because of its similarity to materials used in hydraulic components. The reduced area has a radius of one and a half inches. The diameter of the specimen at the reduced area is one-fourth inch.

All specimens in a particular batch are made from one 36 foot bar. Within a batch, every effort was made to keep the specimen characteristics uniform. The data resulting from this testing is correlated only within a batch, so that it isn't necessary for one batch to be exactly like the next one.

The notch area is not polished, due to the difficulty of getting a reproducible finish by hand. The surface finish on the reduced areas in Lot A was measured using a light section microscope. The detailed findings are discussed in Appendix G. The microscope ridges due to machining were found to have an average height of about 5.8 micrometres with a standard deviation of 1.9. The average width of a ridge was found to be 12.7 micrometers with a standard deviation of 1.23. As an added precaution, each specimen was numbered after its notch area was machined. If the wearing of the tool should have an effect on the surface finish and thus the fatigue life, the failure pattern would be readily detectable.

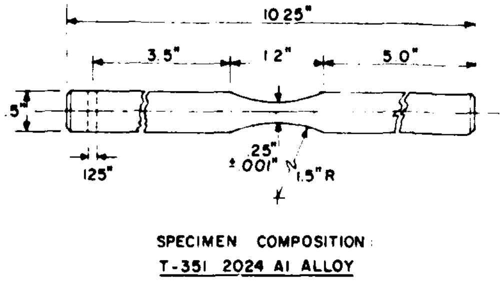


Fig. F-1. Test Specimen Configuration.

APPENDIX G

SURFACE FINISH IN NOTCH AREA OF FATIGUE SPECIMENS, LOT A (1974)

Surface finish measurements for the samples were made with a light section microscope (LSM). The light section microscope allows examination of the surface without touching or altering the surface finish of the samples.

During operations of the LSM, an incandescent lamp illuminates a slit which projects through the objective (O_1) a narrow band of light at 45° to the surface of the sample. (See Fig. G-1.) This band of light is observed through objective (O_2) of the microscope at the opposite 45° angle. Objective (O_2) has the same magnification as objective (O_1).

The fine band of light traces the surface of the sample, showing its peaks and valleys. (See Table G-1.) Measurements of the peaks and valleys are made by using a cross-hair reticle in the eyepiece. The reticle can be shifted within the field of view by turning a graduated cylinder. The cylinder is calibrated so the measured values are read directly in micrometres (μ) at 200x or in half-micrometres at 400x.

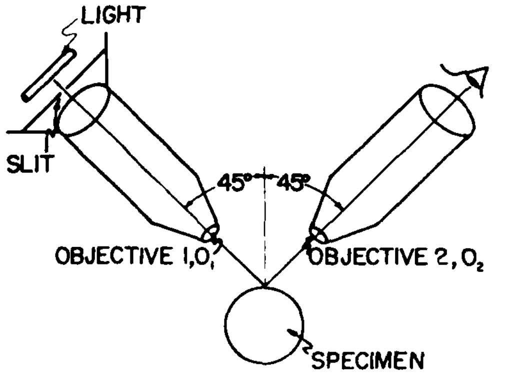


Fig. G-1. Schematic of Light Section Microscope.

The roughness height (R_t) can be determined in the following manner:

1. **The horizontal line of the cross hair is moved to the highest peak of the light by means of the measuring cylinder.**

2. **The graduation on the cylinder is noted, then the cross hair is moved to the lowest point or valley and the graduation is noted. The**

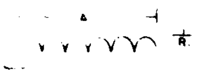
difference between the two readings is the roughness height (R_t).

NOTE: To avoid including the width of the light band in the reading, the horizontal line of the cross hair should be moved from center to center, top to top, or bottom to bottom edge of the peaks and valleys of the light band.

For measuring the roughness width (A_r), the vertical line of the cross hair is used in a similar manner to that for finding (R_t). It is moved from the center of a peak (or valley) across one or several peaks (or valleys).

The measurements of the roughness heights were made at the center of the smallest specimen cross-section and made at random by turning the sample. The roughness width measurements were also made at the approximate center of the reduced specimen area and were made over six peaks and valleys, then averaged. *Observation:* All of the samples measured were fairly uniform on roughness height and the peaks measured were chosen for ease of measurement. Thus, the peaks measured were not the normal (average) surface height but probably represent the worst case in the selected areas.

TABLE G-1. Surface Finish Measurements Results* $R_T(\mu)$, $A_r(\mu)$.**



SAMPLE NUMBER	Ar 6	$R_T(\mu)$						MEAN R_T	[illegible]
		1	2	3	4	5	6		
3**	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.04
8	[illegible]	4.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10	[illegible]	9.0	8.0	[illegible]	[illegible]	[illegible]	10.0	[illegible]	[illegible]
13	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
14	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4.0	[illegible]	[illegible]
17	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
20**	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
22	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
23	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
24	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MEAN Ar 6	[illegible]						Mean-S	[illegible]	[illegible]
[illegible]	[illegible]						S-S	[illegible]	[illegible]

*Mean of max R_T for each sample [illegible]

**Samples had scratches

***Measurements obtained with [illegible]

APPENDIX H

USE OF STRAIN GAUGES ON FATIGUE SPECIMENS

Instead of placing a force transducer in line with the cylinder rod end, selected specimens were made into force transducers by mounting a strain gauge on the top surface adjacent to the reduced diameter. The strain gauges used were micro-measurements FAW-03 "fatigue-life" gauges (100Ω).

The wiring diagram used is the "three-wire" system. (See Fig. H-1.) This arrangement uses a temperature compensating gauge, which is mounted on a non-stressed surface near the active gauge.

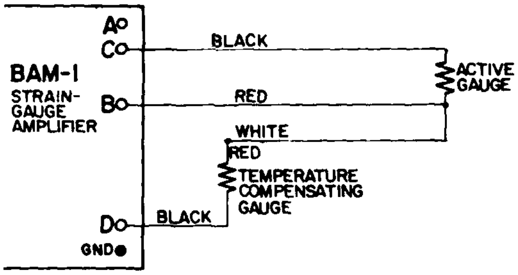


Fig. H-1. Wiring Diagram for Fatigue Specimen Strain Gauge Showing Temperature Compensation Gauge.

APPENDIX I

INSTRUMENTATION USED WITH MARK II TEST SYSTEM

1. **OSCILLOGRAPH RECORDER – Honeywell 1858 CRT Visicorder**

2. **STRAIN GAUGE AMPLIFIER – Vishay Instruments B.A.M.-1**

This amplifier has a high-impedance D-C output for direct connection to an oscillograph recorder and has high stability with a frequency response to 20 KHZ (- 0.5 dB).

3. **STRAIN GAUGES – Micro-Measurements Fatigue Life (FWA-03)**

4. **PRESSURE TRANSDUCER – Pace Model P10-100 Moving-Coil Transducer & Model CD10 Carrier Demodulator**

This system provides a *"noise free"* signal but a slight high-frequency loss. Used for pressure level correlations only.

5. **MULTIMETRICS MODEL AF-420 ACTIVE FILTER**

When calibrating the *peak levels* of strain for side-to-side correlation, this low-pass filter was inserted in the signal outputs. This system was used for peak levels only.

6. **PRESSURE TRANSDUCER – National Semiconductor No. 427 LX14 60A**

The high frequency response characteristics ($\geq$ 20 KHZ) of this transducer with its built-in amplifier provided the necessary frequency response for compatible strain and pressure versus time traces.

APPENDIX J

CHECK LIST FOR INITIATING A FATIGUE TEST

1. Adjust cycle timer to approximately the desired rate.
2. Adjust pressure to its required *"equivalent right-side pressure"* for this cycle rate.
3. Install specimen using alignment tool to achieve alignment accuracy with the cylinder rod. Make sure I.D. numbers are on top.
4. Bring rod end up to specimen.
5. Zero counter.
6. Record elapsed time indicator reading.
7. Start cycling and make recordings of pressure and strain.
8. See Fig. J-1 for limits allowed on cycle timing accuracy.
9. Repeat adjustments on cycle timer and chart recordings until pressure wave form is within limits specified in Item 8. Check air pressure frequently and adjust it within 0.1 psi of required pressure.
10. Log everything, including the strain and pressure traces.
11. Lubricate all rubbing surfaces, including rod end, cylinder seals, etc.

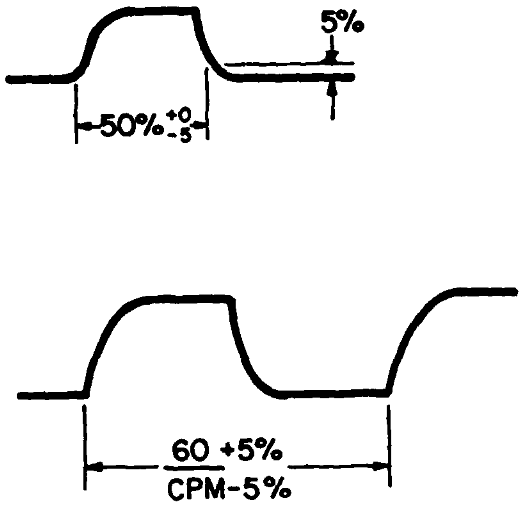


Fig. J-1. Pressure Cycle Time Tolerances.

12. Lubricate system daily and adjust pressure if necessary. Log any adjustments or changes, date and initial them.

13. Before leaving the test area, verify that the micro-switch over-ride is disabled.

APPENDIX K

CHECK LIST FOR CORRELATING BOTH SIDES OF MARK II TEST SYSTEM

1. Set up calibration specimen on right side.
2. Turn on all equipment and zero the BAM-1. Let all equipment warm up for three hours.
3. Adjust all connections for minimum noise.
4. Adjust air pressure on right side to ______ psi.
5. Adjust cycle timer to approximately 60 cpm.
6. Allow specimen to cycle five minutes while adjusting the air pressure.
7. Stop cycling, pull rod end away from specimen. Re-zero strain gauge amplifier
8. Take recordings of zero signals of pressure and strain.
9. Push rod end back to specimen
10. Cycle specimen for five minutes while making fine adjustments of the air pressure.
11. Record traces of pressure and strain cycles.
12. Figure '*span*' of strain signal from any peaks of the wave form to the zero line
13. Turn bridge power off. Place calibration specimen on left side. Turn bridge power back on.

14. Adjust left cycle timing.

15. Stop cycling. Pull rod end away from specimen.

16. Re-zero amplifier and take "*zero*" recording.

17. Make rod end touch specimen and cycle for five minutes.

18. Take strain trace and check "*span.*"

19. Adjust air pressure and repeat strain recording until the strain span for the left side is equal to that on the right. Note the resultant air pressure. This is the air pressure on the left that "*equals*" the strain-inducing pressure on the right for 60 cycles/minute.

20. For 240 cycles/minute on either side, this procedure should be repeated at this rate until the strain spans are equal.